Increased crop damage in the U.S. from excess precipitation under climate change

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Keywords: Agriculture, Maize production, Climate change, Extreme events, Precipitation, Crop damage, Insurance

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Abstract

Recent flooding and heavy precipitation events in the U.S. and worldwide have caused great damage to crop production. If the frequency of these weather extremes were to increase in the near future, as recent trends for the U.S. indicate and as projected by global climate models (e.g., US National Assessment, 2000; IPCC, 2001), the cost of crop losses in the coming decades could rise dramatically. Yet current assessments of the impacts of climate change on agriculture have not quantified the negative effects on crop production from increased heavy precipitation and flooding (Reilly et al., 2001). In this work, we modify a dynamic crop model in order to simulate one important effect of heavy precipitation on crop growth, plant damage from excess soil moisture. We compute that U.S. corn production losses due to this factor, already significant under current climate, may double during the next thirty years, causing additional damages totaling an estimated $3 billion per year. These costs may either be borne directly by those impacted or transferred to governmental insurance and disaster relief programs.

Acknowledgements

We wish to thank three anonymous reviewers whose comments helped to greatly improve this manuscript. This research was supported by Environmental Defense, and carried out by the Climate Impacts Group at the Goddard Institute for Space Studies. E. Mills was supported by the U.S. Environmental Protection Agency.

Running Title: Increased crop damage from excess precipitation

Introduction

Recent data show that total annual precipitation and extreme precipitation events have increased in the U.S. and in other parts of the world during the last century, especially in the last two decades (Karl, 1998; Milly et al., 2002), often resulting in large crop losses and other flood-related damages (Chagnon et al, 1997; Pielke and Downtown, 2001). While showing a cause–and-effect relationship between precipitation increases and flood-related damage is difficult due to concurrent changes in population growth, economic development, flood-control infrastructure and early-warning efforts, currently observed trends toward increased precipitation and more extreme events are projected to intensify under future climate change, leading to higher flooding probability (Palmer and Räisänen, 2002), and thus increased damage to agricultural production compared to present (IPCC 2001; Reilly et al., 2001).

Under current climate conditions, damage to agricultural production due to excess precipitation events can be substantial. For example, the 1993 U.S. Midwest floods caused damages to farmers valued at about $6-8 billion (Newsweek, July 19, 1993), a figure that was roughly 50% of total losses from the flood. Agricultural production was also negatively impacted by the North Dakota Red River floods of 1997, which caused total damage of roughly $1 billion (Spring Flood Information, 2001). Red River and Mississippi floods occurred again in 2001, delaying planting.

Excess soil moisture, in addition to direct flood damage, is a major component of crop losses due to extreme precipitation events. Excessively wet soils directly damage crops both above and belowground because of anoxic conditions (Kozdrój and van Elsas, 2000); increased risk of plant disease and insect infestation (Ashraf and Habib-ur-

Rehman, 1999); and delayed planting or harvesting due to inability to operate machinery. During the 1993 Mississippi floods, about 70% of total crop losses occurred in upland areas due to saturated soils from sustained heavy rains. In the last twenty years, excess soil moisture cost Iowa farmers five times more than direct flood damage, according to crop insurance data (Rain and Hail Insurance Service, historic database).

To buffer themselves from losses associated with these and other types of extreme events, such as hail damage, U.S. farmers typically turn to crop insurance. A portion of the costs for this and other types of disaster assistance (relief, loans, etc.) is borne by State and Federal governments, because private firms often find the associated risks too unpredictable to insure at market prices (Van Schoubroeck, 1997; Mills et al., 2001; Vellinga et al., 2001; see also: www.ers.usda.gov/publications/aer774/aer774.pdf for an overall discussion of risk management and the role of Federal crop insurance). Total Federal disaster-related payments in the U.S. amounted to $119 billion over the period 1993-1997, while crop insurance losses grew 10-fold in recent decades (Anderson, 2000). In the year 2000, a total of 205 million acres were insured through the Federal Crop Insurance Corporation. Losses paid to farmers last year totaled over $2 billion, out of $34 billion of insurance coverage. Total losses paid to farmers via this program were $21 billion in the period 1981-2000. (USDA Risk Management Agency, 2001). An increase in extreme precipitation events under climate change will likely increase payments from government programs.

Despite the risk of increased crop losses due to flooding and excess precipitation under climate change, the potential damage to agricultural production is not well quantified in state-of-the-art assessments of agricultural production. As discussed in the recent U.S. National Assessment of the Potential Consequences of Climate Variability and Change--Agriculture Sector Report (Reilly et al., 2001), this "methodological lapse" stems in part from the fact that crop damage from flooding and excess soil moisture is not well simulated by today's dynamic crop models (e.g., see Fig. 1). Indeed, in a recent inter-comparison study (Paustian et al., 2000), researchers using these models failed to simulate the reductions in U.S. Midwest corn yields observed in 1993. The crop models used in the U.S. National Assessment have shown only positive impacts of increased precipitation on U.S. rain-fed maize production, linked to increased soil water availability under climate change (Reilly et al., 2001; Tubiello et al., 2002).

In order to quantify the importance of including the effects of excess soil moisture on current and projected future crop production, we present herein results of a simplified modeling experiment. We focus on the direct negative effects of excess soil moisture on crop yield, under current and future climate regimes. Potentially positive adjustments to regional production under climate change, linked to market mechanisms and/or to technological adaptation, are not considered.

Our approach is based on the development of new computational rules modifying an existing model of maize (CERES-Maize; see Tsuji et al., 1994), in order to limit plant growth in the presence of prolonged exposure to excess soil moisture conditions. Using the modified model, we then repeated the U.S. National Assessment simulations of rain-fed maize production at nine sites in the American Midwest, under current and projected future climate conditions. Our methodology and simulation results are compared to those previously obtained using the unmodified crop model, and discussed in this short communication.

Materials and Methods

We modified CERES-Maize, a crop model widely used to assess the impacts of climate change on maize growth and yield (see for example: Rosenzweig et al., 1995) to additionally simulate crop damage due to excess soil moisture from heavy precipitation. CERES-Maize, used in the recent U.S. National Assessment study (Tubiello et al., 2002), is a dynamic crop model that calculates plant development, growth, and final yield as a function of weather (air temperature, precipitation, solar radiation), crop genetic traits (such as cultivar-specific length to maturity and grain filling rates), and management practices. The latter include planting date, row spacing, irrigation and fertilization application, etc. (Tsuji et al., 1994). In addition to plant growth and development, the crop model computes daily soil-water balance, used in the computation of plant drought stress. In contrast, no stress to plant growth is computed by CERES-Maize under prolonged conditions of excess soil water.

In order to simulate negative effects on maize growth and yield caused by excess soil moisture, we modified the original model by introducing a damage function that limited the simulated plant's ability to grow roots after three consecutive days of continued soil saturation (Bennicelli et al., 1998; Ashraf et al., 1999). By virtue of the dynamic nature of the crop model considered, limits to root growth cause temporary restrictions to water, nutrient, and carbon movement through the simulated soil-plant system, reducing water transpiration, biomass production and ultimately grain yield, compared to plant growth under normal soil water conditions.

Although the simulated plant dynamics following root growth restrictions were consistent with the findings of the few experimental studies published (e.g., Bennicelli et al., 1998), the new model used herein should be seen as a simple illustrative tool, used to provide insight into the importance of simulating damage to crop yield from excess soil moisture conditions. To this end, we conducted a new set of crop simulations, originally performed during the U.S. National Assessment, and compared performance of the original and modified CERES-Maize models.

Model Calibration. We simulated dryland maize growth and yield in the U.S. Corn Belt at nine sites in Kansas, Illinois, Indiana, Iowa, North and South Dakota, Ohio, and Wisconsin. Soil, climate, and crop management input data were those specified in the U.S. National Assessment study. The original model had already been calibrated and evaluated at those sites, using county-level reported yields (Tubiello et al., 2002). We calibrated the modified CERES-Maize model under current climate conditions at Des Moines, IA, using observed county-level yields for the period 1951-1998. At this calibration site, reported yield statistics showed a -30% yield anomaly, compared to the long-term mean, in correspondence to the 1993 U.S. Midwest floods. The original CERES-Maize model was unable to simulate such effect. In contrast, by appropriately calibrating the damage function described above, the modified CERES-Maize was able to compute a 23% reduction of yield in 1993.

Because the modifications of the crop model only affect performance under rare extreme precipitation events, overall original and modified models performed similarly compared to observed data (see Tab. 1). The modified model improved yield predictions in years characterized by high precipitation during the growing season. For the other (non-calibrated) sites also affected by the 1993 flooding, yield predictions with the modified model were in better agreement with reported data.

The difference of the yields predicted with the two model versions was thus chosen to indicate yield reduction, or damage, due to the simulated effects of excess soil moisture. Figure 2 shows a comparison between simulated and reported damage by a crop insurance company due to excess soil moisture (www.rainhail.com). Overall correlation between simulated and reported damage was high (r=0.90). The model was able to simulate the 1993 flooding effects, as well as other damage events, in 1980, 1986, 1990, and 1998, in good agreement with the reported losses. The model was unable to reproduce damage in 1984 and 1991, most likely because heavy rains occurring earlier than in the other years delayed planting, reducing yields in a way not simulated by our model.

Results and Discussion

When averaged over the entire study period (1951-1998) and all study sites, our calculations indicated that, under the current climate regime, the negative effects of excess soil moisture on maize yields was relatively low over the long term, or about 3% (i.e., from Table 1, computed difference between original and modified model simulations), reflecting the fact that extremely heavy precipitation events are rare under current climate conditions. Nonetheless, considering that the current production value for U.S. maize is about $20 billion a year (USDA National Statistics, 2001), a 3% factor corresponds to losses of $600 million per year on average. If extended to the other major U.S. crops (wheat, cotton, soybean, and potato), which have a current total value of $50 billion a year, our simulations imply that current U.S. crop damage from excess soil moisture is currently about $1.5 billion per year, on average. This figure for agriculture is about one-third of total economic losses due to heavy precipitation and flooding in the U.S. (estimated at about $4 billion per year (Federal Emergency Management Agency,FEMA, 1998)) and is consistent with available data from the USDA Risk Management Agency. The long-term averaged numbers we discussed above should not be considered as small, especially when compared to the total annual output of U.S. agriculture. Long-term averages were computed in order to further compare damage estimates made with the modified model with reported national data; it should not be overlooked that these small background figures correspond to very large losses clustered in time around a few highly damaging extreme events (i.e., the 1993 floods).

Using the methodology described above, we proceeded to estimate the potential impacts of excess soil moisture on U.S. crop yields under climate change. We used the same GCM climate change scenarios, produced by the Hadley and Canadian Climate Centres, as done in the U.S. National Assessment (e.g., Reilly et al., 2001). Both scenarios projected increases in total precipitation as well as in the number of extreme precipitation events for the continental U.S. Averaged over the study sites used in this work, the number of extreme precipitation events (with total precipitation above 25 mm, 50mm, and 75 mm, respectively) were higher than present by 30% in 2030, and by 65% in 2090. As a result, the reduction of maize yields due to excess soil moisture conditions—computed using the modified model—was larger under climate change conditions than we had estimated under current climate. Naturally, due to the very nature of extreme events and their low impact on long-term average yields, the use of the modified model did not change the U.S. National assessment results concerning the *mean* positive direction and magnitude of the impacts of projected climate change on U.S.

maize production. However, simulations with the modified model, when compared to results obtained with the original CERES-Maize, showed that the *probability* of damage due to excess soil moisture could be 90% greater in 2030, and 150% greater in 2090, compared to present conditions. Focusing on the near future only, our projections indicated that by 2030, U.S. maize production losses due to extreme precipitation events and excess soil moisture could nearly double from today's levels. Based on our previous extrapolation to total U.S. long-term agricultural damage, we thus project that increased precipitation events in the U.S. could lead on average to losses of ~ $3 billion per year by the 2030s, due to increased excess soil moisture conditions.

Finally, our simulations also indicated that, under the projected climate change scenarios, the distribution of damaging events would be progressively skewed towards the occurrence of greater loss, compared to today (Fig. 3). We computed that the probability of events causing damage comparable to, or greater than, the 1993 U.S. Midwest floods will double by 2030 and quadruple by 2090, compared to present.

Model Limitations

A number of considerations may limit the application of our modified CERES-Maize model as a tool for systematically assessing crop damage from increased excess soil moisture conditions under climate change. First, the small number of experimental data available limited our ability to test model performance at the plant level. Second, our simulations, just as those performed for the U.S. National Assessment, assume that county-level crop production can be approximated, at least in the mean, by site-level simulation results. Weather and topographic properties specific of one study site were used to describe an ensemble of weather and topography--and the associated yields— that characterize a county. Such approximations tend to generate larger climate sensitivity in modeled data compared to observed. We conclude that our simulated effects of excess soil moisture on crop yields may be overestimates when extended to the county level. Third, because delayed planting due to wet soils also reduces crop yields, a mechanism for simulating delayed planting by a "smart farmer" needs to be implemented within our model, in order to improve the comparison between simulated and reported yields.

Finally, this study was not coupled to a regional economic model. Our computations of economic cost due to increased extreme precipitation events under climate change may thus be overestimates, as they assume no technological change or adaptation compared to present conditions.

Conclusions

Our simulations show that it is possible to quantify the effects of excess soil moisture to crop production by modified dynamic crop models. Furthermore, simulations with our own modified version of CERES-Maize illustrate how exacerbated conditions of excess soil moisture under climate change, arising from an increased frequency of extreme precipitation events, may add significant negative pressure on maize yields, farm production levels and farmers in the U.S. Midwest. Additional negative effects linked to extreme precipitation events, such as direct physical damage to crop plants form heavy rains and hail, were not included in this study. Despite the necessity of further model development, our results clearly indicate that the corresponding additional economic costs to crop production can be significant, given the considerable losses already incurred by farmers under the current climate regime. Efforts in model development are thus needed to include these effects in crop models for use in impact assessment studies under climate change. Ignoring such damages may lead to overestimates of the positive impacts of “wet” scenarios of climate change on rain-fed agriculture around the world.

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Table 1. Observed yields and simulation results with original (ORIG.) and modified (MOD.) CERES-Maize, at nine simulation sites in the U.S.. Corn Belt.

Averages of maize yields (t ha^{-1}) for the period 1951-1998. Root mean square errors for each set of simulations are also indicated. The difference between original and modified model simulations of yield represents damage due to excess soil moisture (average for all sites: 3%)

SITES	OBS.	ORIG.	RMSE	MOD.	RMSE
Des Moines, IA	8.4	8.6	1.5	8.3	1.5
Peoria, IL	8.9	8.3	1.8	8.0	1.9
Indianapolis, IN	8.2	9.2	1.6	9.0	1.4
Madison, WI	7.8	8.4	2.5	8.1	2.5
Kansas City, MO	6.5	8.1	2.1	7.9	1.9
Sioux Falls, SD	6.2	8.2	2.2	8.0	2.1
Columbus, OH	7.5	8.2	1.8	8.2	1.8
Fargo, ND	5.6	5.8	1.4	5.6	1.3
North Platte, NE	8.2	7.7	1.2	7.4	1.2
MEAN	7.5	8.1	(1.8)	7.9	(1.7)

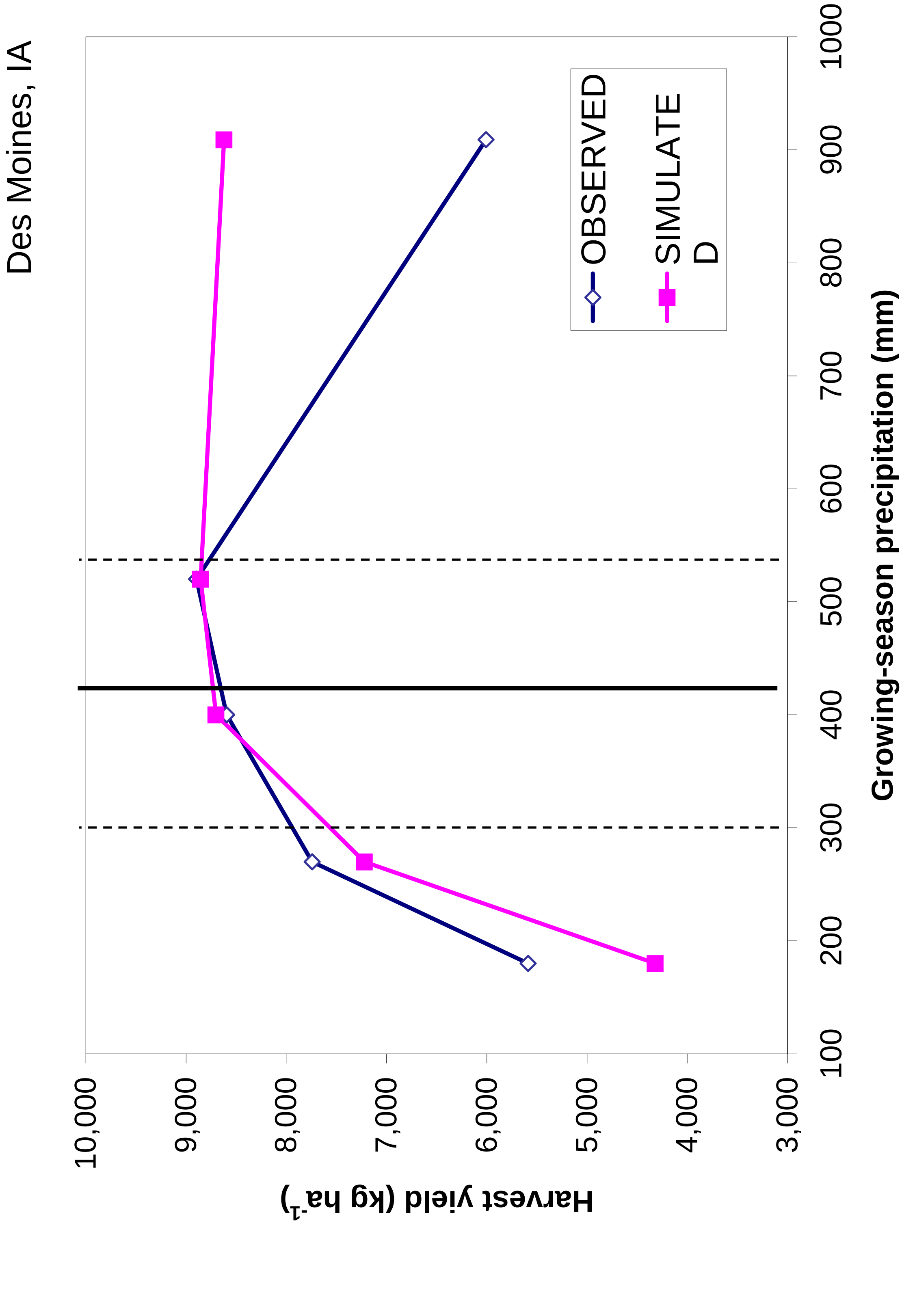
Figure Legends

Figure 1. Unmodified crop model and observed response to precipitation during the growing season. Simulations were performed using the CERES-Maize model, without excess soil moisture effects on crop growth and yield. Input data taken from the U.S. National Assessment study, showing simulated versus county-level yields of corn for the period 1951-1998 at Des Moines, IA. Solid vertical line represents the mean growing season precipitation over the reported period and dotted lines its standard deviation.

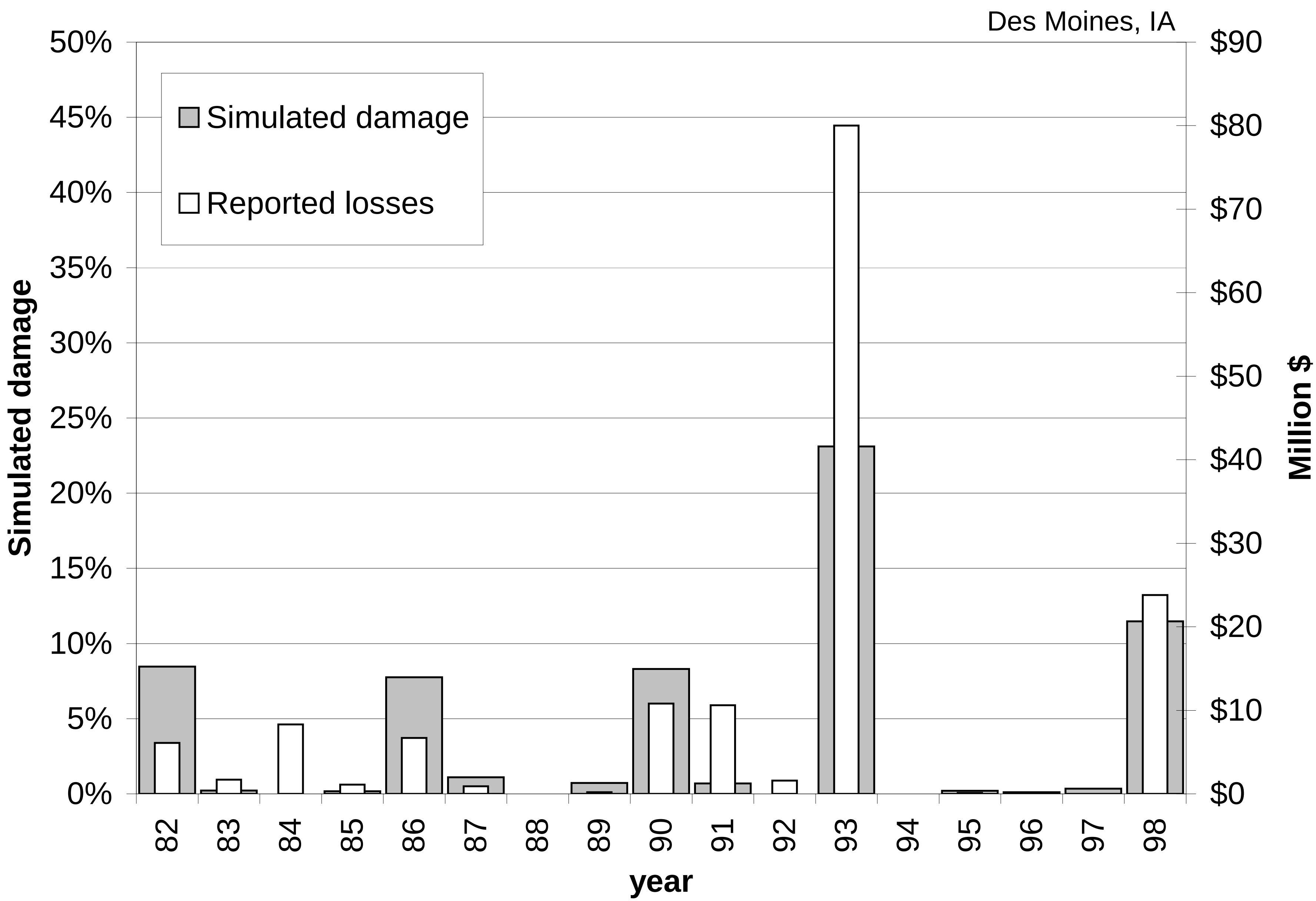
Figure 2. Reported losses in corn production due to excess soil moisture in Polk County, IA, compared to model-simulated crop damage. The latter is expressed as the percent difference between the original and the modified CERES-Maize models, for each simulated year.

Figure 3. Number of events causing damage to maize yields due to excess soil moisture conditions, averaged over all study sites, under current baseline (1951-1998) and climate change conditions. The Hadley Centre (HC) and Canadian Centre (CC) scenarios with greenhouse gas and sulfate aerosols (GS) were used. Events causing a 20% simulated yield damage are comparable to the 1993 U.S. Midwest floods.

Figure 1



Des Moines, IA
OBSERVED
SIMULATED
Harvest yield (kg ha^{-1})
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
100
200
300
400
500
600
700
800
900
1000
Growing-season precipitation (mm)


Des Moines, IA
Simulated damage
Reported losses
Simulated damage
Million $
year
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
82
83
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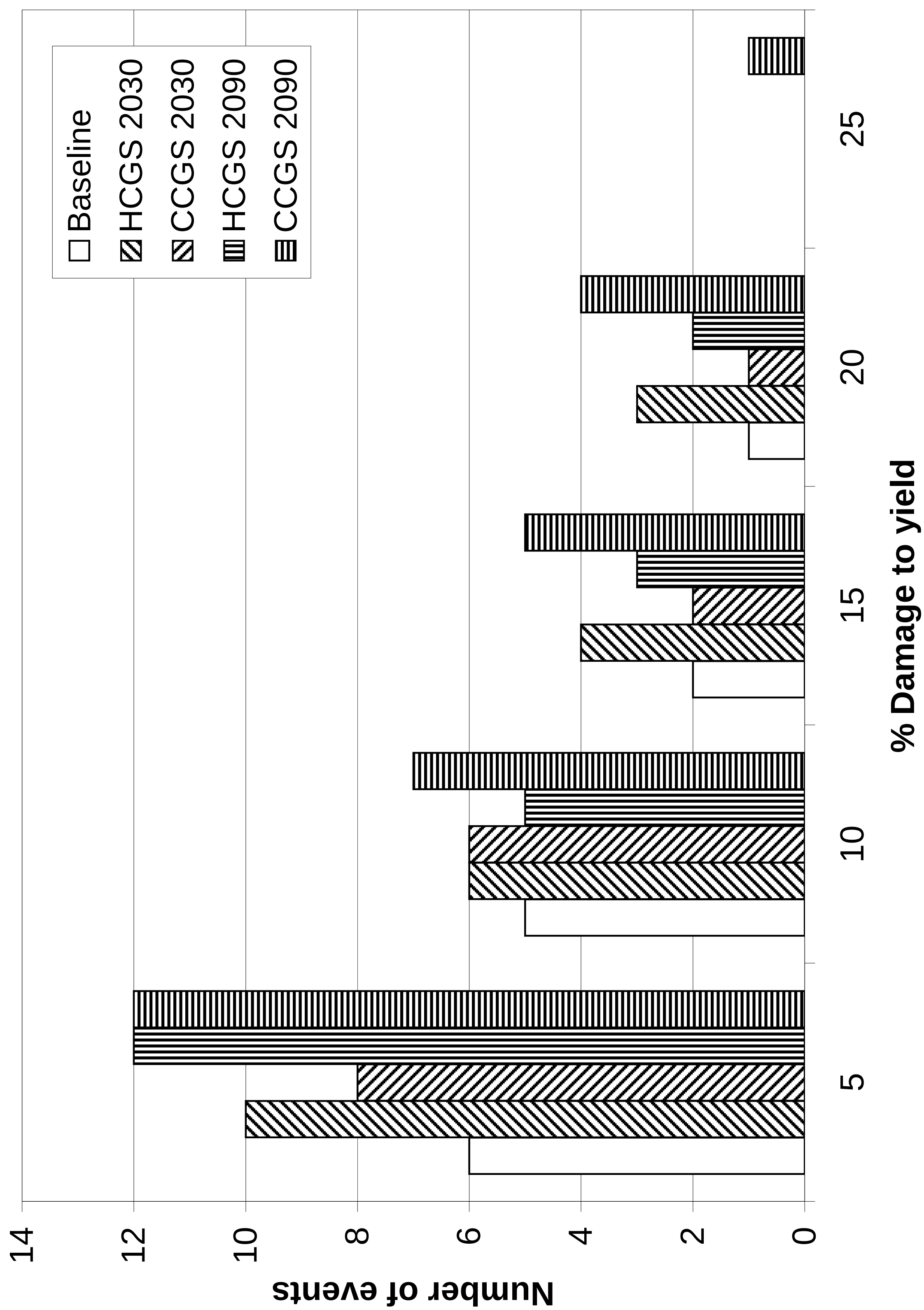
97
98

Figure 2

Figure 3


Number of events
0
2
4
6
8
10
12
14
5
10
15
20
25
% Damage to yield
Baseline
HCGS 2030
CCGS 2030
HCGS 2090
CCGS 2090